Multi-Wavelength Mode-Locked Laser Arrays for WDM Applications

L. Davis, M.G. Young, D. Dougherty, S. Keo, R. Muller, P. Maker
Center for Space Microelectronics, Jet Propulsion Laboratory
California Institute of Technology
4800 Oak Grove Drive
Pasadena, CA 91109 USA

ABSTRACT

Multi-wavelength arrays of colliding pulse mode-locked (CPM) lasers have been demonstrated for **wavelength division multiplexing (WDM)** applications. Arrays with up to 9 wavelengths have been fabricated, operating at repetition rates of ~ 18 GHz with pulsewidths < 10 ps.

Introduction: The need for increased bandwidth is driving the development of both increased speed in time division multiplexing (TDM) and more channels in WDM for fiber optic communication systems. While present WDM systems utilize discrete DFB lasers, future high speed systems would greatly benefit from an integrated, multi-wavelength source of optical pulses at very high repetition rates for WDM soliton communications. Mode-locked lasers are a potential source at high repetition rates (>10 GHz), where monolithic cavities can be easily fabricated with reasonable cavity lengths (<5 mm). In our work, the CPM configuration for the mode-locked lasers has been chosen due to the prediction [1] and demonstration [2] of stable, short pulse output that can be used successfully in transmission systems [3]. We have extended previous work on CPM lasers to multi-wavelength laser arrays, where the center wavelength of each device is adjusted by a DBR grating in the cavity.

Device fabrication: The monolithic CPM laser is fabricated using two MOCVD growths. The first growth is a separate confinement heterostructure with 4 compressively strained (ε=1%) quantum wells at 1.55 μm and confined on either side by 1200 Å of InGaAsP (λ=1.2 μm). After the diffraction gratings were written by direct write electron beam lithography and etched into the SCH region, the upper cladding and contact layers were grown. The lasers were fabricated into a 3.5 μm wide ridge laser structure with a continuous active region. As seen in Fig. 1, the symmetric 4.6 mm long ridge was divided into 5 sections with 3 contacts: the two end sections are 75 μm each and contain the gratings; the two gain sections are 2180 μm; and a center saturable absorber section of 50 μm. The sections are separated by four 10 μm wide gaps, and electrical isolation of ~ 1kΩ is achieved between the sections by etching the InGaAs contact layer. The fabrication of a microwave ground-signal-ground (GSG) contact for the saturable absorber allows for high frequency probing. A continuous gain region has been employed for ease of fabrication and the elimination of multiple reflections within the cavity.

Device performance: The threshold current for uniformly pumped devices without gratings is approximately 120 mA. Devices with gratings show thresholds of 135 - 155 mA depending on the lasing wavelength with respect to the gain peak. When a reverse bias is applied to the saturable absorber, the devices exhibit passive mode-locking for a range of gain currents and saturable absorber voltages. Typical operating currents are in the range 165-210 mA and typical saturable absorber voltages are –0.5 to –2.0 volts. The devices mode-lock best near threshold (as seen in [2]), and have facet powers of ~ 1mW at the optimal operating points. Fig. 2 shows the modulation response of the CPM lasers under mode-locking conditions. Outside the mode-locking regime of operation, the RF spectra shows a distinct peak at both the cavity fundamental of 9.03 GHz and at the mode-locking frequency of 18.06 GHz. Under the proper bias conditions, the device mode-locks at 18.06 GHz with removal of the CW component, and the 9.03 GHz peak is strongly (> 30 dB) suppressed. A bias tee attached to a high frequency probe is used to supply both the DC reverse bias and a sinusoidal clock signal at 18.06 GHz to the saturable absorber of each device to reduce the phase noise and jitter. Phase noise close to and far from the carrier as a function of the applied RF power has been measured, and all the devices show a sharp reduction in the single side-band (SSB) phase noise with an increase in the applied RF power. At 20 dBm input power and 100 kHz offset, the SSB phase noise is as low as -107 dBc/Hz, limited by the RF source (HP 83731B + 8349B amplifier).

For dense WDM applications, we have demonstrated a 5 element array of mode-locked lasers, with the wavelength separation between devices designed for 5 ps pulsewidths. For a transform limited 5 ps optical pulse at 1.55 μm, the required FWHM spectral bandwidth is 0.63 nm (79 GHz @ 1.55 μm) assuming a $sech^2$ shape [4]. The 20 dB down spectral bandwidth is then 2.5 nm (313 GHz). To conform to the multiples-of-100 GHz ITU standard, the wavelength channels for the devices were designed to have the next larger spacing, which is 3.2 nm or 400 GHz. The combined optical spectra of the five element array is shown in Fig. 3 with no current tuning, with an average channel spacing of 3.3 nm. All wavelengths are within the erbium doped fiber amplifier (EDFA) gain bandwidth. Arrays up to 9 adjacent elements have been demonstrated, although the spectrum is not as evenly spaced due to gain pulling effects. While other multi-wavelength transmitters have been demonstrated for soliton generation [5], to the best of our knowledge these are the first multi-wavelength arrays of mode-locked lasers. Tunability of the individual devices over as much as 125 GHz is provided by forward biasing the grating contact (0-15 mA), but is limited by the presence of gain material in the grating region. Fig. 4 shows the pulsewidth, spectral width and the time bandwidth product for all the channels of a 9 element array designed for 200 GHz spacing. The pulsewidth for all the channels is less than 10 ps, limited by the intracavity grating. As seen by us and others [2], similar devices without gratings in the cavity have shown pulsewidths less than 2 ps. The time bandwidth product for these array devices is approximately 1.5-2 times the transform limit. Further optimization of the length and strength of the diffraction grating will allow for more accurate channel spacing and reduction of the spectral bandwidth per channel.

Conclusion: We have demonstrated what we believe to be the first multi-wavelength arrays of mode-locked lasers for WDM applications, with up to 9 wavelengths in the EDFA gain bandwidth operating at ~18 GHz on a single chip. All the channels have pulse widths less than 10 ps. These high performance arrays are potential sources in future soliton-based WDM communication systems.

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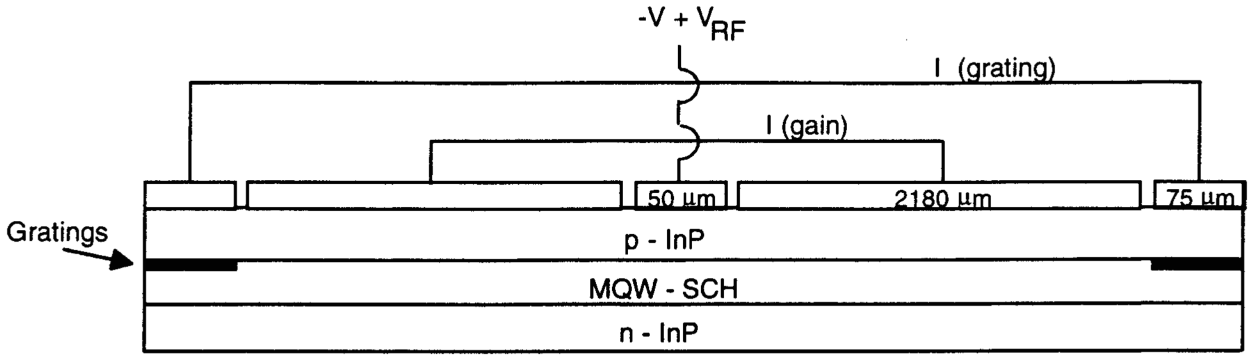
Fig. 1 Schematic diagram of the symmetric 4.6 mm mode-locked laser cavity.

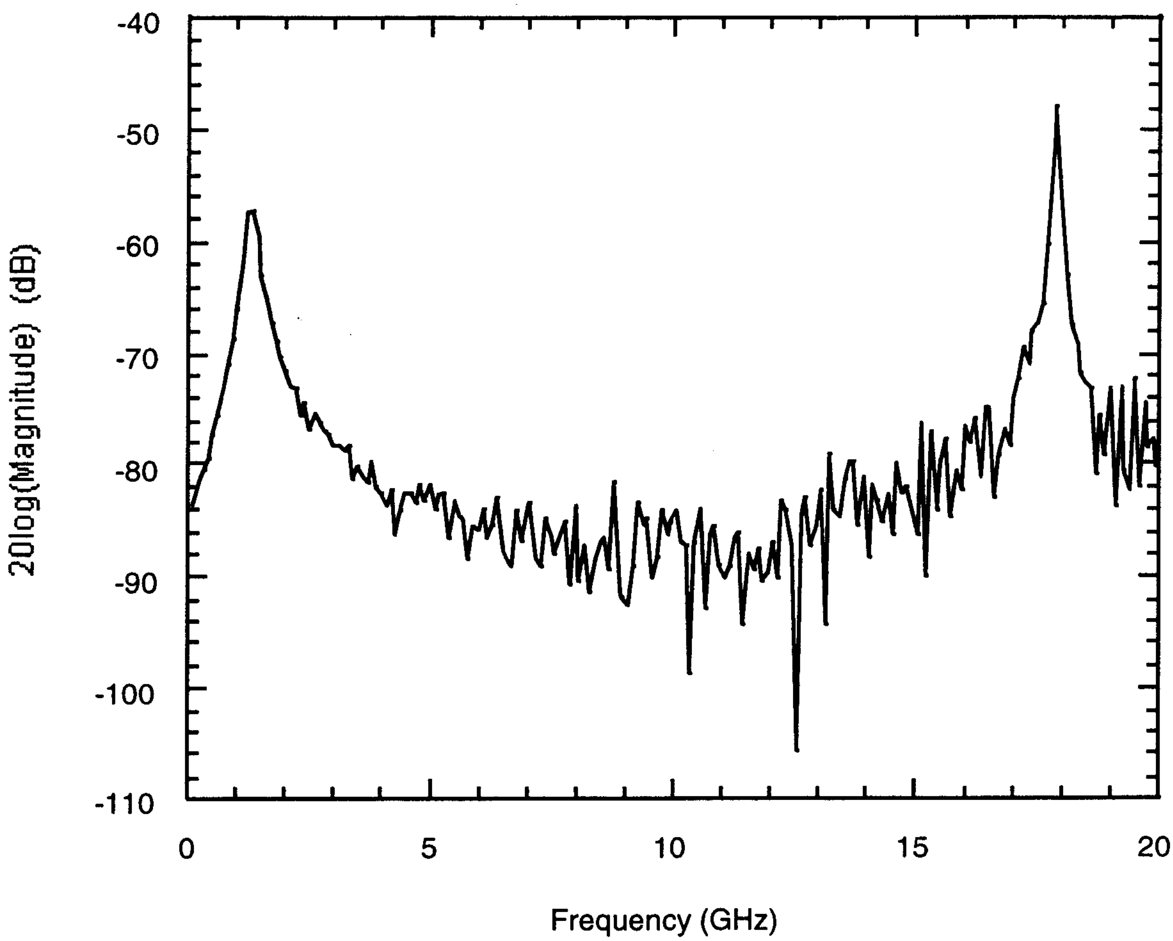
Fig. 2 The modulation response of the mode-locked laser showing the complete suppression of the fundamental of the cavity at ~ 9 GHz .

Fig. 3 Optical spectrum of a five element mode-locked laser array designed to be on 400 GHz (3.2 nm) spacing.

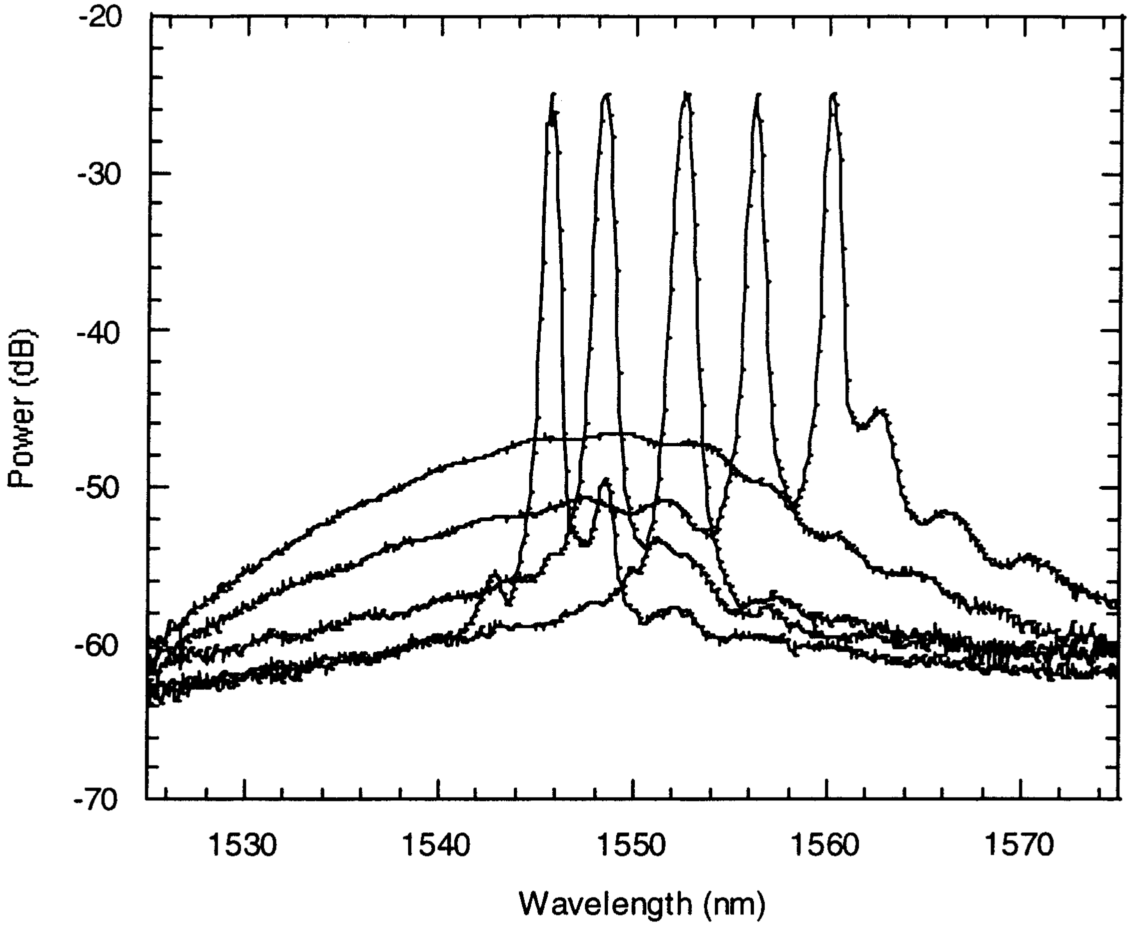
Fig. 4 The pulse width, spectral width and time bandwidth product for a nine element mode-locked laser array. The dashed line indicates the transform limit of the time bandwidth product assuming a $sech^2$ pulse shape.



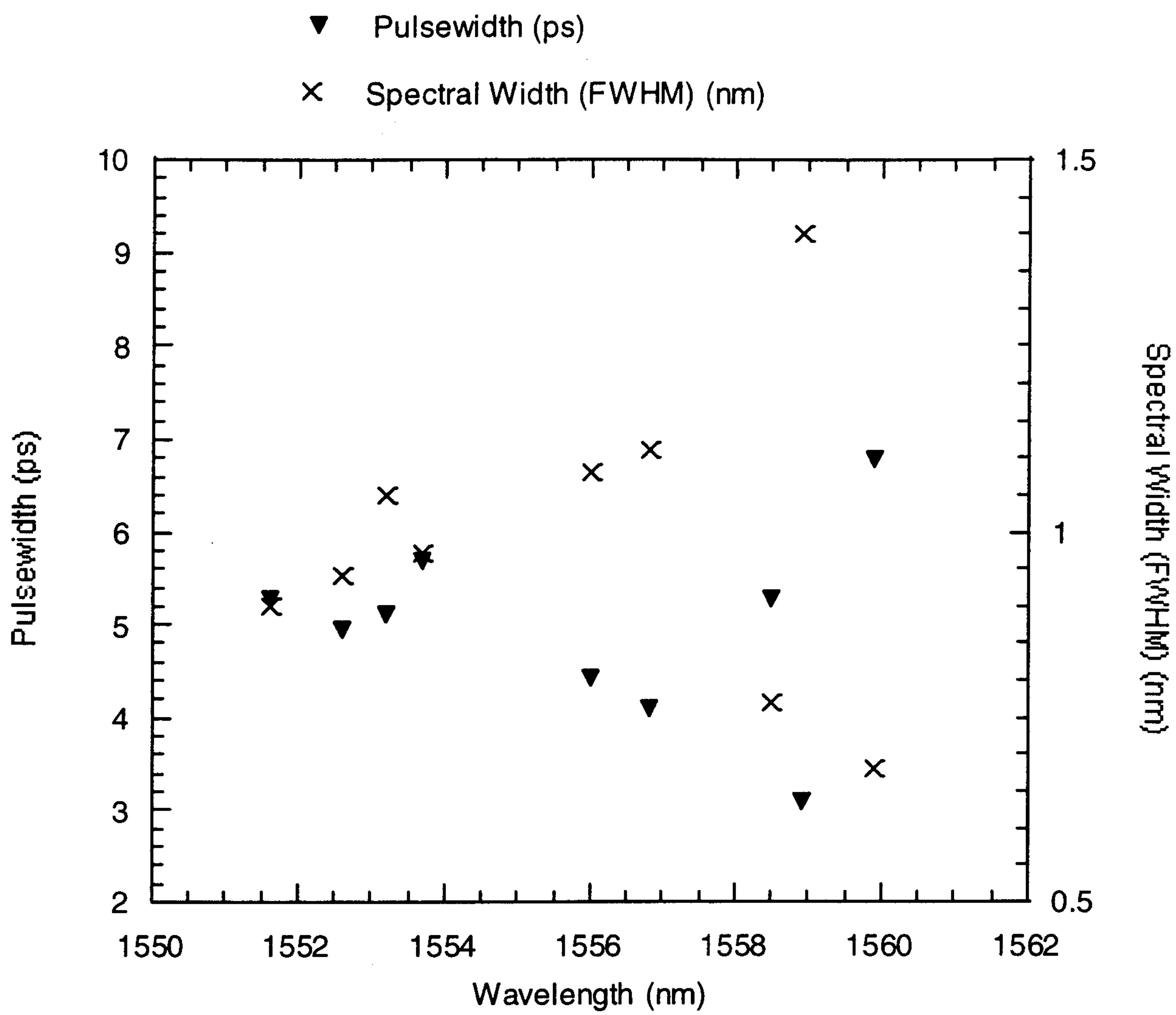
-V + V
RF
I (grating)
I (gain)
50 µm
2180 µm
75 µm
Gratings
p - InP
MQW - SCH
n - InP



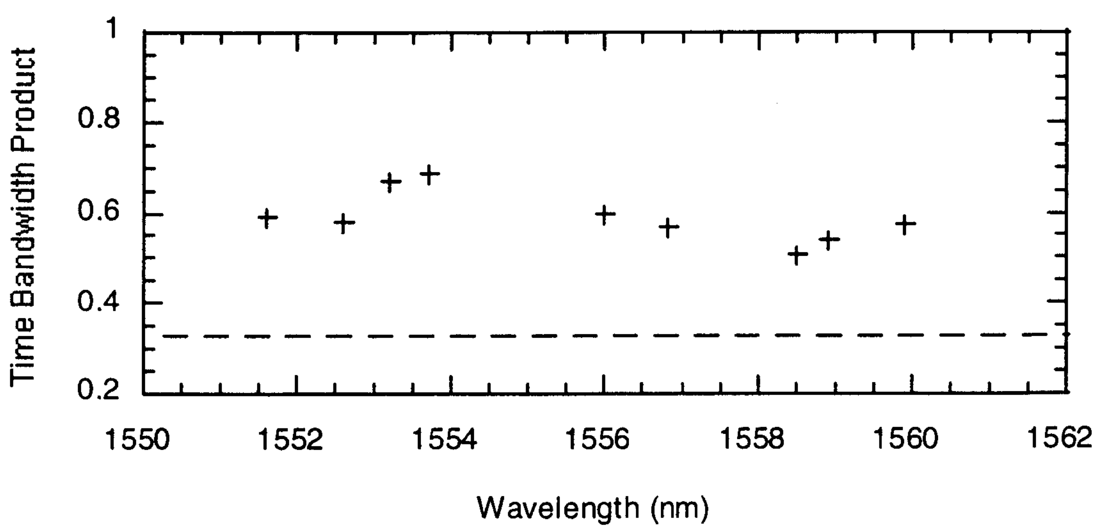
-40
-50
-60
-70
-80
-90
-100
-110
20log(Magnitude) (dB)
0
5
10
15
20
Frequency (GHz)



-20
-30
-40
-50
-60
-70
Power (dB)
1530
1540
1550
1560
1570
Wavelength (nm)



Pulsewidth (ps)
Spectral Width (FWHM) (nm)
10
9
8
7
6
5
4
3
2
1.5
1
0.5
Pulsewidth (ps)
Spectral Width (FWHM) (nm)
1550
1552
1554
1556
1558
1560
1562
Wavelength (nm)



1
0.8
0.6
0.4
0.2
Time Bandwidth Product
1550
1552
1554
1556
1558
1560
1562
Wavelength (nm)